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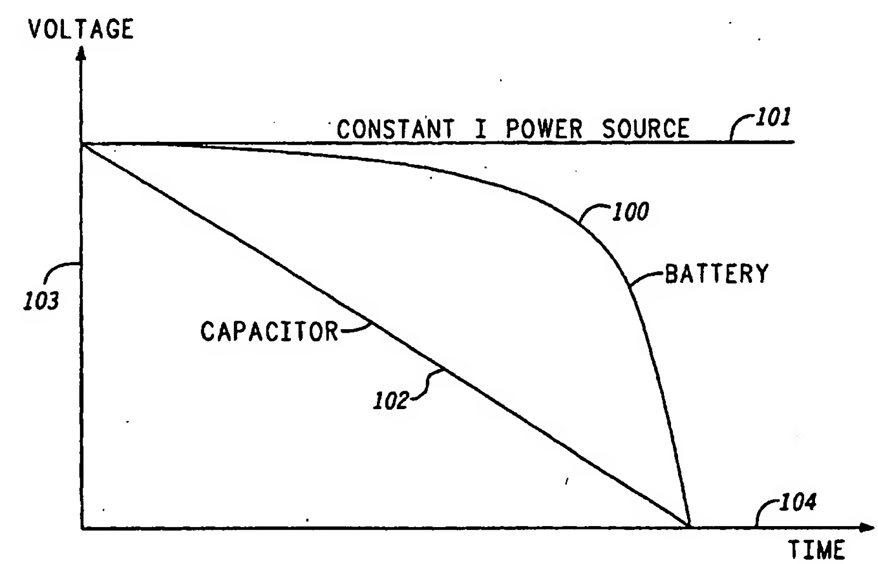
(54) Title: MODULARIZED BATTERY MODELS FOR ELECTRONIC CIRCUIT SIMULATORS



(57) Abstract: A battery model for circuit simulation is provided. The battery model comprises a transmission line type network. The network includes a non-standard particle that represents physical properties, chemical properties, ionic and atomic transport properties, charge and discharge rates, temperature and history of usage of rechargeable cells. The model can be represented as a graphical icon within the circuit simulator. The model allows accurate representation of battery cells. The model is a modularized mathematical model that can be programmed using a circuit simulator's structure and language. This invention breaks the continuous mathematical model into pieces that are digestible by common circuit simulators.

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Modularized Battery Models for Electronic Circuit Simulators

TECHNICAL FIELD

This invention relates in general to electronic circuit simulators, and, more specifically, to electronic circuit simulators which simulate circuits including battery cells

BACKGROUND

Several decades ago, when people designed electronic devices and circuits, the only way to determine if an idea actually worked was to physically build and test the circuit in the lab. For example, if someone conceived an idea for a new flashlight, one needed connect actual wires to a bulb, battery and switches in order to prove that the idea was viable. Thus, a physical prototype served as a 'test of truth' for any idea.

With the advent of semiconductor devices, electronic circuits became more complex. Special test boards called "bread boards" or "proto boards" were developed to help scientists and engineers build prototypes. These bread boards were constructed with many electrically connected holes, into which parts, wires, switches and the like could be inserted. By pushing parts into the holes, the need for solder was eliminated, thereby saving time. Complex circuits often had wires running in numerous directions and thus resembled the nests built by rats. Finished prototype circuits were, in fact, often called "rat's nests".

Advances in technology created needs for increasingly complex circuits. As the number of transistors in a circuit grew into the millions, it became nearly impossible for a person to interconnect millions of parts together without making a mistake. It therefore became

economically difficult to construct complex prototypes in order to prove the workability of an idea.

The advent of personal computers alleviated this problem. Software programs called "simulators" were written which mathematically modeled electronic devices like transistors, switches, capacitors and resistors. Now scientists and engineers could build greatly complex circuits by writing computer programs called "simulations". The simulations could predict voltage levels, current levels, and time responses to external stimuli.

With the development of "windows" type systems, with graphical interfaces, scientists and engineers no longer had to write programs to simulate circuits. Instead, one merely "pointed and clicked" with a mouse, thereby dragging and icon onto a virtual schematic diagram. For example, if one wanted to connect a resistor, they pointed at a symbol that looked like a resistor and dragged it onto a piece of virtual paper. They then drew wires with a virtual pen that connected the resistor icon in place. The simulator then assembled code from the picture that had been drawn, and then simulated the circuit. This is how simulations are still done today.

Simulations, however, are not perfect. In fact, in order to speed up the computations, simplified mathematical models are used. For example, as opposed to carrying out computations to 10 decimal places, assumptions of accuracy are made and the machine may actually only use two decimal places. This reduction in computation time allowed simulators to run faster, as computing power was limited in the early days of computers.

Similar approximations are made regarding electrical elements. For example, batteries are often modeled as ideal voltage sources. Everyone knows that a real battery will run down and die after it has been used extensively. An ideal voltage source lasts indefinitely! Also, real batteries contain a limited amount of energy. For instance, it is well known that a car cannot be started with a AA size battery because it does not contain enough energy. Ideal sources, however,

store infinite amounts of energy. For these reasons, ideal sources are generally not good models of real batteries.

With the development of rechargeable batteries, electronic circuits are being designed which charge these batteries. These circuits still have to be built by hand and can not be simulated because ideal sources do not accurately model real battery cells. Physically building test circuits is both slow and expensive.

Some battery models have been created. U.S. Patent 5,428,560, Serge, et al. describes a hardware simulator for a battery. The term "hardware" is meant to mean an actual circuit, as opposed to a software model. U.S. Patent 4,499,552, Kanazawa, also discloses a hardware simulation. These hardware models are generally large and complex. Additionally, they do not accurately model the chemical reactions that take place within a battery. They are primarily designed to provide a physical circuit with power. They are therefore not suitable for accurate simulation.

There is therefore a need for an electronic circuit simulator model that accurately simulates real battery cells.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates the discharge behavior or a power source, a capacitor and a battery.

Figure 2 is a transmission line type network in accordance with the invention.

Figure 3 is a schematic diagram of a battery model in accordance with the invention.

Figure 4 is a modularized presentation of a particle in accordance with the invention.

Figure 5 is experimental data of an example where the invention is charged and discharged at a C/3 rate.

Figure 6 is experimental data of an example where the invention is charged and discharged at a 1 C rate.

Figure 7 is experimental data of an example where the invention is loaded with a pulse discharge.

Figure 8 is experimental data of an example where the invention is loaded with a multi-pulse discharge.

Figure 9 is a table of battery model parameters.

SUMMARY OF THE INVENTION

This invention includes a battery model for electrical simulators. The battery model is a mathematical representation of a real world rechargeable battery cell. The model is based upon physical properties, chemical properties, ionic and atomic transport properties, charge and discharge rates, temperature and history of usage of rechargeable cells.

The model is constructed by using a transmission line type network consisting of electronic simulator elements including resistors and capacitors. Additionally, a third element, referred to herein as a particle, is also included to round out the model. The particle component implements known differential equations into the electronic simulator. The transmission line network, made of a module that includes two resistors, a capacitor and a particle, is then repeated for better accuracy, in order to model the cathode and electrode of a battery. A separator is modeled in between as a resistor.

This invention allows circuits including batteries to be modeled accurately in electronic simulators, thereby reducing the design cycle time for electrical circuits by achieving realistic simulation results. The invention also reduces or eliminates the need for hardware prototype builds in the design phase. The battery model is a first principle calculation, which simulates the cell electrical behavior from the physical-chemical phenomena that occur within a battery. The battery behavior is represents a mathematical model of electrochemical kinetics, ion transport properties, thermodynamic data and cell specifications.

The invention also includes an icon that can be dragged graphically into a circuit.

DETAILED DESCRIPTION OF THE INVENTION

Portable wireless communication circuit designs depend on the battery performance. However, there are no realistic battery models in current, commercially available electronic circuit simulators. Most circuit simulations are performed assuming an ideal constant voltage power source with no regard for the impact of load current and usage history. In real life, portable electronic devices utilize batteries with a finite energy capacity, voltage, and impedance characteristics. These characteristics change with current, temperature, and history of usage. In the absence of the present invention, the most accurate way to test a circuit design with batteries is to actually build hardware with real batteries.

It is well known that the behavior of electrical and electronic components can be described quantitatively with mathematical equations. Thus, many sophisticated circuit simulation software packages have been developed and now are commercially available for circuit design and simulation. Examples of commercially available circuit simulators include Advanced Design System (ADS) and Microwave Design System (MDS), manufactured by Hewlett Packard, Saber, manufactured by Analogy, and PSpice, manufactured by MicroSim.

As previously stated, these simulators, ADS, MDS, PSpice or Saber, lack accurate models or components to represent batteries. The closest approximation that can be found in the simulators are either voltage and current source or capacitors.

Referring now to figure 1, therein is shown a comparison of the discharge behavior of a battery 100, an ideal voltage source 101, and a capacitor 102. The vertical axis 103 represents voltage, while the horizontal axis 104 represents time. As can be seen, the discharge characteristics are remarkably different. The battery discharge curve 100 and the capacitor discharge curve both represent finite electrical energy storage devices, which means that the voltage eventually reaches zero. However, the capacitor discharge curve 102 is proportional to time, while the battery discharge curve 100 is non-linear. The ideal voltage source curve 101

represents an "infinite" capacity, as indicated by the fact that the voltage stays constant across time. As can clearly be seen in figure 1, neither a capacitor nor an ideal voltage provides an accurate representation of a battery.

In the past, mathematical battery models have been developed by scientists at academic institutions. These mathematical models have been written as stand alone programs in common computer languages like FORTRAN and C. Such models have been used for gaining a better understanding of the physical and chemical phenomenon associated with a battery. They have also been used by cell manufactures as a tool to build better cells.

These complex, stand alone computer programs are not suitable for electronic simulators, as the code generally includes numerous calculations of differential equations. Electronic circuit simulators require separate modules and circuit components that must be sequentially connected. The academic mathematical programs use continuous analysis and all equations are solved simultaneously.

This invention is an electronic circuit model that is a modularized mathematical model that can be programmed using a circuit simulator's structure and language. This invention breaks the continuous mathematical model into pieces that are digestible by common circuit simulators.

To better understand the invention a brief background of battery parameters is helpful. The characteristics of a physical battery are dependent on many parameters. These include, for example: 1) Chemistry: Lithium Ion, Lithium Polymer, nickel metal hydride, and Nickel cadmium batteries all exhibit different types of characteristics under charge and discharge conditions. 2) Discharge/Charge rate: Batteries are limited by maximum practical discharge/charge rates. The effective battery capacity depends upon this rate. The higher the rate is, the smaller the capacity will be. 3) Temperature: The power and capacity of batteries decline when the temperature drops. Batteries tend to have a much stronger temperature dependence than do normal electronic components. 4) History of usage: A battery has a limited cycle life. The

effective capacity and output voltage are both degraded as the battery is cycled (charged and discharged) repeatedly. In order to be effective, battery models should represent these characteristics.

As mentioned, mathematical battery models have been developed in academic institutions and the equations governing chemical operation of battery cells are understood. For example, T.F. Fuller, M. Doyle and J. Newman, disclosed such a mathematical model in the Journal of Electrochemical Society, Vol. 141, No. 1, page 1, 1994. Similarly, D. Fan and R. White disclosed another model in Vol. 138, No. 1, 1991 of the same publication.

The present invention takes advantage of the accuracy of such mathematical models in electronic simulators by constructing them as electronic modularized components and networks. In order to achieve the non-standard electrical functions, e.g. the differential equations, a particle component was created to represent electrode materials and ion transport processes in a real battery. The boundary conditions for the differential equations in the mathematical models are also represented in the present invention.

A battery cell typically consists of a cathode, an anode and a separator. The separator is generally present, however it is not mandatory. Referring now to figure 3, a battery cell model 300 consisting of a cathode 301, an anode 302 and a separator 303 are illustrated. The cathode 301 is the positive electrode and the anode 302 is the negative electrode. The voltage across the battery cell model 300, as well as other parameters, is dependent upon the electrode material systems.

The electrodes consist of densely packed powder particles that are soaked with electrolyte. Referring now to figure 2, illustrated therein is a circuit model of a battery in accordance with the present invention. The circuit is represented as a transmission line type network. The basic building block 200, which is repeated, consists of a unit solid electrode material resistor, Rs 201; a unit liquid electrolyte resistor, RL 204; a unit solid/liquid interface double layer capacitor, Cdl

202; and a unit electrochemical reaction parameter, Pa 203. This combination 200 can represent either a single electrode material particle or a group of these particles. The components Rs 201, RL 204 and Cdl 202 are regular electronic circuit elements, and are available in most circuit simulators. The component Pa 203 is a non-standard element that is described by equations 1-6 that are described in subsequent sections of this description. The values of Rs 201 and RL 204 depend on the conductivity of the electrode materials and electrolyte, respectively. The number of the repeating units 200 is dependent upon the specific battery system as well as the desired accuracy of the simulation. In the present invention, both the cathode (301 of figure 3) and the anode (302 of figure 3) are represented by the repeated block 200 illustrated in figure 2. The separator (303 of figure 3) is represented by a resistor.

As stated, the model makes use of the mathematical theory of battery cells, via the particle element. It is explained as follows: Electrical energy is stored in battery electrode materials as chemical energy. In order to achieve high energy density and power density, the electrode materials are composed of small particles comprised of atoms of the electrode soaked in electrolyte. When the battery is either being charged or discharged, electrons, atoms, and ions are transported to/from the surface of the particle where electrochemical reactions take place to generate current flow. Therefore, the fundamental element of the battery model is a mathematical representation of the ionic or atomic transport processes and reactions in a solid particle.

To illustrate this phenomena, a lithium ion battery will be used as an example. The key variable in the calculation is the concentration of lithium in a solid particle. This concentration determines the electrode voltage and current rates of change with respect to time.

The active material is assumed to be made up of spherical particles of radius, R_s, with diffusion being the mechanism of transport of the lithium into the particle. Establishing a coordinate systems with the direction normal to the surface of the particles to be the r-direction,

the rate of change in concentration with respect to time can be expressed by the following equation:

$$\frac{\partial C_s}{\partial t} = D_s\left[\frac{\partial^2 C_s}{\partial^2 t} + \frac{2}{r}\frac{\partial C_s}{\partial r}\right] \qquad (1)$$

where Cs and Ds represent the concentration and diffusion coefficient of lithium in the solid particle phase. The symmetry of a sphere sets the following boundary condition:

$$\frac{\partial C_s}{\partial r} = 0 \qquad \text{at } r = 0 \qquad (2)$$

The second boundary condition is provided by a relationship between Faraday charge transfer current density across the liquid/solid interface, j, and the rate of diffusion of lithium ions into the surface of insertion material:

$$j = -FD_s\frac{\partial C_s}{\partial r} \text{ at } \qquad r = Rs \qquad (3)$$

where F is the Faraday constant.

The open-circuit potential, U, of insertion materials varies with amount of lithium inserted and is expressed by a general function of composition in the particle

$$U = Uo + f(Cs) \qquad (4)$$

The Faraday charge transfer current density can be represented by

$$j = i_o \{\exp[\alpha F/RT(\eta\text{-}U)] - \exp[-\alpha F/RT(\eta\text{-}U)]\} \quad (5)$$

where i_o is the exchange current density, α is the charge transfer coefficient, and η is the overpotential that is defined by

$$\eta = \Phi_1 - \Phi_2 \quad (6)$$

where Φ_1 is the solid phase potential and Φ_2 is the electrolyte phase potential.

The key to accurate battery simulation is to calculate the lithium concentration that is determined by equation 1. In order to solve the Eqns. 1-3, we further divide a particle into many layers, as illustrated in Fig. 4.

Referring now to figure 4, a layered model 400 of a particle is shown. Here, each module 402, 403 represents a layer of solid material with unit length and is described by equation 1 above. The number of the modules depends upon the particular battery system that is being simulated, as well as and the desired accuracy of the simulation

The center layer 404 and surface layer 401 of the module 400 are represented by the boundary conditions of equations 2 and 3, respectively. The key variable, lithium concentration, C_s, is passed from one module to the next one through the connection 405 between the two components 401,402.

Many battery parameters, including thermodynamic relationships, kinetic constants material parameters, and battery design parameters can be included in the model by the programmer who incorporates the model into a circuit simulation package. Additionally, certain parameters will be set by the user prior to simulation. A table of these parameters can be seen in figure 9. These include a name for the battery model, a capacity, and a state of charge. The

capacity is a representation of energy, but is usually expressed in terms of Amp-hours, as the battery has a specified voltage. The state of charge is a number between 0 and 1, with 1 being 100% charged and 0 being 0% charged. Commonly used batteries could easily be built into a library that could be accessed within the simulator.

The present invention can be incorporated into any electronic simulator. In the initial reduction to practice, the model was constructed in the Saber electronic circuit simulator, manufactured by Analogy. The model was constructed by writing executable code in a nodal entry type format. This code was attached to a battery icon such that it could be dragged with a mouse into any electrical circuit.

The advantages of the present invention are numerous. First and foremost, the invention allows scientists and engineers to simulate electronic circuits with batteries that include a finite capacity, initial state of charge, and other physical parameters. Second, the invention allows frequency analysis for accurate modeling of pulse charge and discharge circuits.

The invention further allows accurate analysis of radio frequency circuits, microprocessor shutdown circuits, and the like. The invention allows enhanced predictability of failure modes as well.

The present invention includes a battery model that is a first principle calculation, The invention simulates the cell electrical behavior from the physical-chemical phenomena which occurs within a battery. Battery behavior is accurately represented by a mathematical model of electrochemical kinetics, ion transport properties, thermodynamic data and cell specifications.

The invention may be further understood by way of an example, and further in consideration of experimental results of such an example. Using the present invention, the electrical behavior of a 9mm Lithium-Ion (Li-Ion) battery manufactured by Sony, Inc. was simulated. This battery is a typical battery which can be found in cellular phones manufactured

by Motorola, Inc. The Saber Simulator running on a Hewlett Packard workstation computer was used for the simulation.

Referring now to figures 5 and 6, the DC charge/discharge behavior of the simulated Sony 9mm Li-ion battery is shown therein. This behavior is shown at both a C/3, in figure 5, and 1 C rate, in figure 6, where C is the rated capacity of the battery in milliamp-hours. In other words, where the capacity is 1 Amp-hour, the charging current used to charge and discharge cell is 1 Amp, at a 1 C rate, and 1/3 of an Amp at a C/3 rate. These figures show both the actual charge and discharge of a real cell and the simulated results. As can be seen by examining the figures, the simulation fits the experimental curves very well. The model fits both high rate (1C) and low rate (C/3) behavior with same set of parameters.

Referring now to figure 7, illustrated therein is the comparison of experimental and simulation results for an i1000 phone pulse on Sony9mm Li-ion battery. The i1000 is a digital phone manufactured by Motorola, Inc. When a digital phone transmits, it draws a pulsed current load from the battery. This is of particular importance, as real batteries exhibit voltage drops during high current pulses. Prior art battery models, including, voltage sources, capacitors and current sources, were unable to predict the physical response of a real cell. As can be seen in figure 7, the present invention models the physical cell. This is a fundamental advantage of the present invention over the prior art.

Referring now to figure 8, illustrated therein is the i1000 phone's multi-pulse behavior on both a real and simulated Sony9mm cell. It can be seen that the simulated pulse discharge behavior predicts the performance of the physical cell.

The computer simulation time for each curve in figures 7 and 8 is less than one minute. It can thus be inferred that the cycle time of circuit designs comprising a real battery can be significantly reduced by using the present invention.

While the preferred embodiments of the invention have been illustrated and described, it is clear that the invention is not so limited. Numerous modifications, changes, variations, substitutions, and equivalents will occur to those skilled in the art without departing from the spirit and scope of the present invention as defined by the following claims. For example, while the invention has been cast as a four component module 200 shown in figure 2, that is stepped and repeated, the module consisting of two resistors, a capacitor and a particle, it is contemplated that circuit equivalents for this construction, e.g. transistors instead of resistors, would produce the same result.

What is claimed is:

1) A battery model for electrical circuit simulators, comprising software code that simulates the performance of a real battery.

2) The battery model of claim 1, wherein the battery comprises a graphical icon on a computer display, the icon being movable into a graphical circuit representation.

3) The battery of claim 1, where in parameters for the software code are selected from the group consisting of chemistry, manufacturer, capacity, state of charge, temperature, life cycle, conductivity of materials, concentration of electrolyte, exchange current density, diffusion coefficients, double layer capacitance, particle size, surface area, density, porosity, electrode thickness, separator thickness, and mass ratio.

4) A battery model for electrical circuit simulators, comprising at least one electrode.

5) A battery model as in claim 4, wherein one electrode comprises a cathode.

6) A battery model as in claim 5, wherein the cathode comprises at least one module.

7) A battery model as in claim 6, wherein the at least one module comprises:

A) at least one electrode material resistor;

B) at least one electrolyte resistor;

C) at least one interface capacitor; and

D) at least one particle.

8) A battery model as in claim 7, wherein the at least one particle represents a combination atomic and ionic transport processes.

9) A battery model as in claim 8, wherein the at least one particle further represents differential equations.

10) A battery as in claim 5, wherein one electrode comprises an anode.

11) A battery model as in claim 10, wherein the anode comprises at least one module.

12) A battery model as in claim 11, wherein the at least one module comprises:

E) at least one electrode material resistor;

F) at least one electrolyte resistor;

G) at least one interface capacitor; and

H) at least one particle.

13) A battery model as in claim 12, wherein the at least one particle represents a combination atomic and ionic transport processes.

14) A battery model as in claim 13, wherein the at least one particle further represents differential equations.

15) A battery model as in claim 14, further comprising a separator.

16) A battery icon for electrical circuit simulators, the icon being representative of a circuit comprising at least one electrode.

17) A battery icon as in claim 16 wherein one electrode comprises a cathode.

18) A battery icon as in claim 17 wherein one electrode comprises an anode.

19) A battery icon as in claim 18, wherein the cathode comprises a first at least one module, and further wherein the anode comprises a second at least one module.

20) A battery icon as in claim 19, wherein the at least one module comprises:

A) at least one electrode material resistor;

B) at least one electrolyte resistor;

C) at least one interface capacitor; and

D) at least one particle.

21) A battery icon as in claim 20, wherein the at least one particle represents a combination of atomic and ionic transport processes.

22) A battery icon as in claim 21, further comprising a separator.

23) A method for simulating battery circuits, the method comprising the steps of:

A) Providing an electrical circuit simulator;

B) Providing a battery model having a cathode, an anode and a separator; and

C) Connecting the battery model to an electrical circuit by normal means;

wherein the battery model will simulate battery behavior represented by physical and chemical reactions.

24) A method of designing an electronic circuit, comprising:

A) inputting parameters into a battery model for electronic circuit simulators;

B) simulating a circuit in an electrical circuit simulator; and

C) using data from the simulation to design a real circuit.

25) A module for building a battery for electrical circuit simulators comprising at least one element selected from the group consisting of an electrode material resistor, a liquid electrolyte resistor, a solid to liquid interface capacitor and an electrochemical reaction particle.

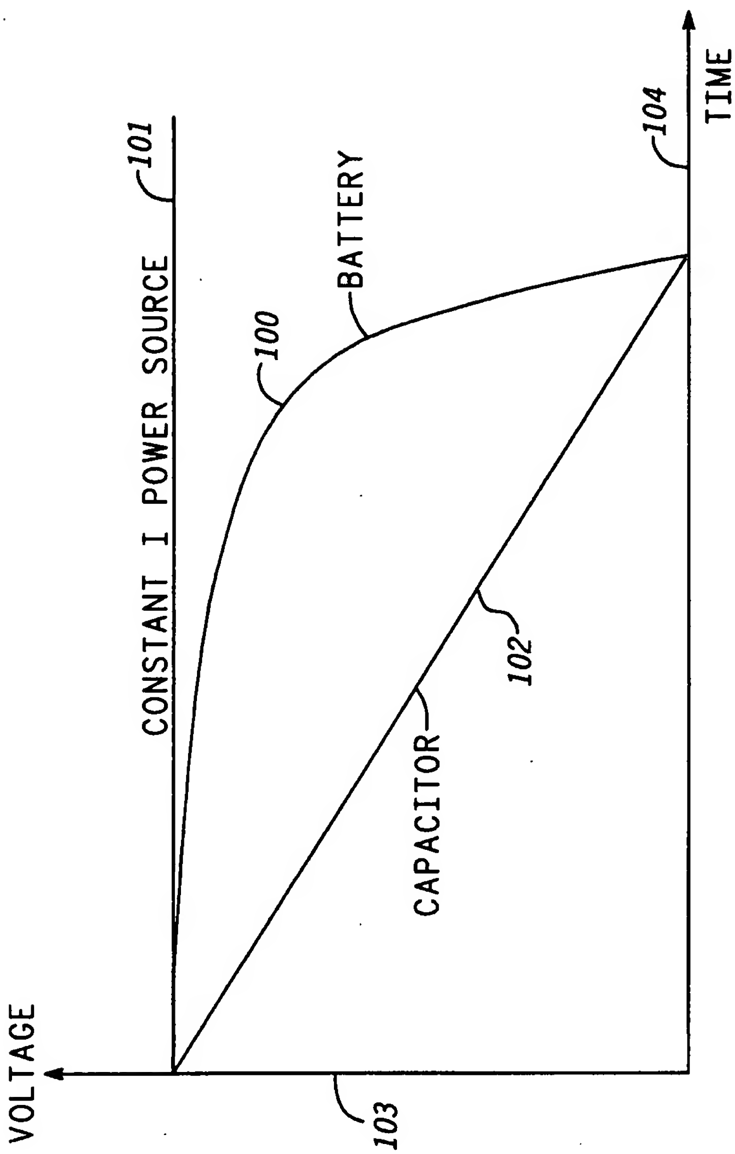
VOLTAGE
TIME
CONSTANT I POWER SOURCE
101
100
BATTERY
104
102
CAPACITOR
103

FIG. 1

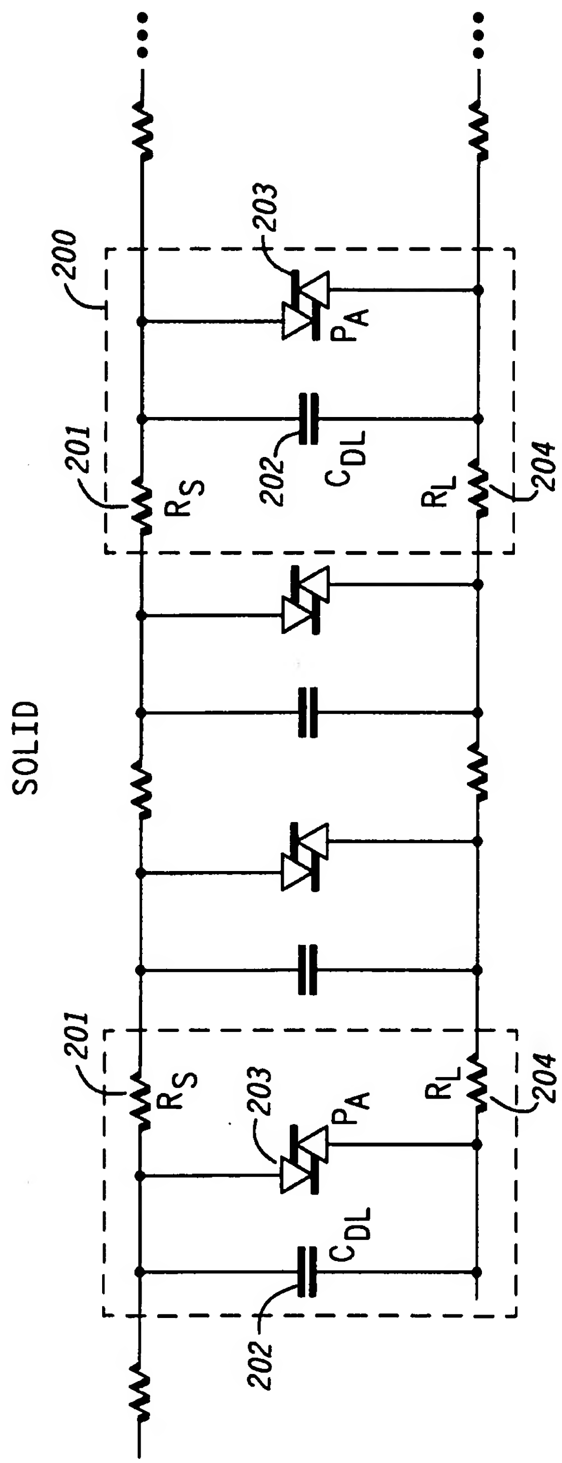

FIG. 2

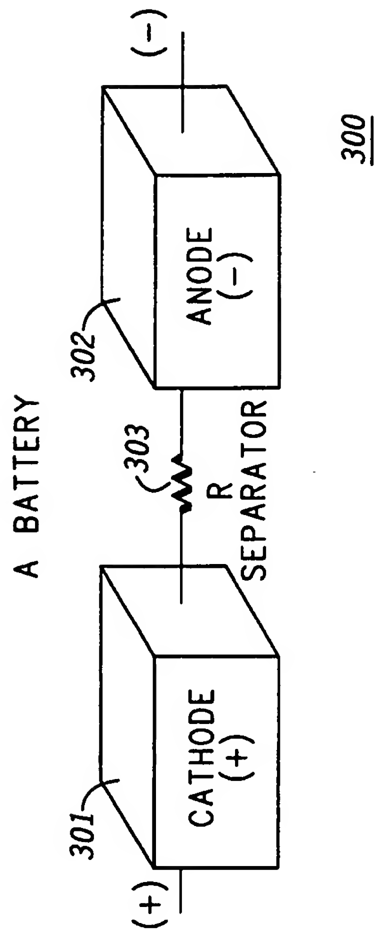
A BATTERY
(+)
301
CATHODE
(+)
303
R
SEPARATOR
302
ANODE
(−)
(−)
300

FIG. 3

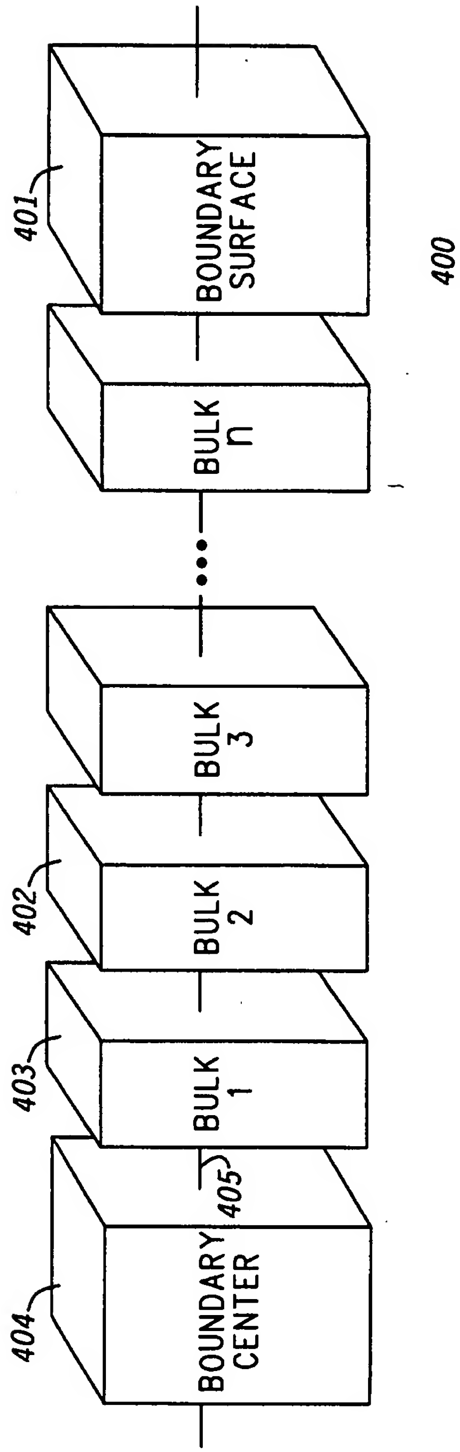
404
BOUNDARY
CENTER
405
403
BULK
1
402
BULK
2
BULK
3
BULK
n
401
BOUNDARY
SURFACE
400

FIG. 4

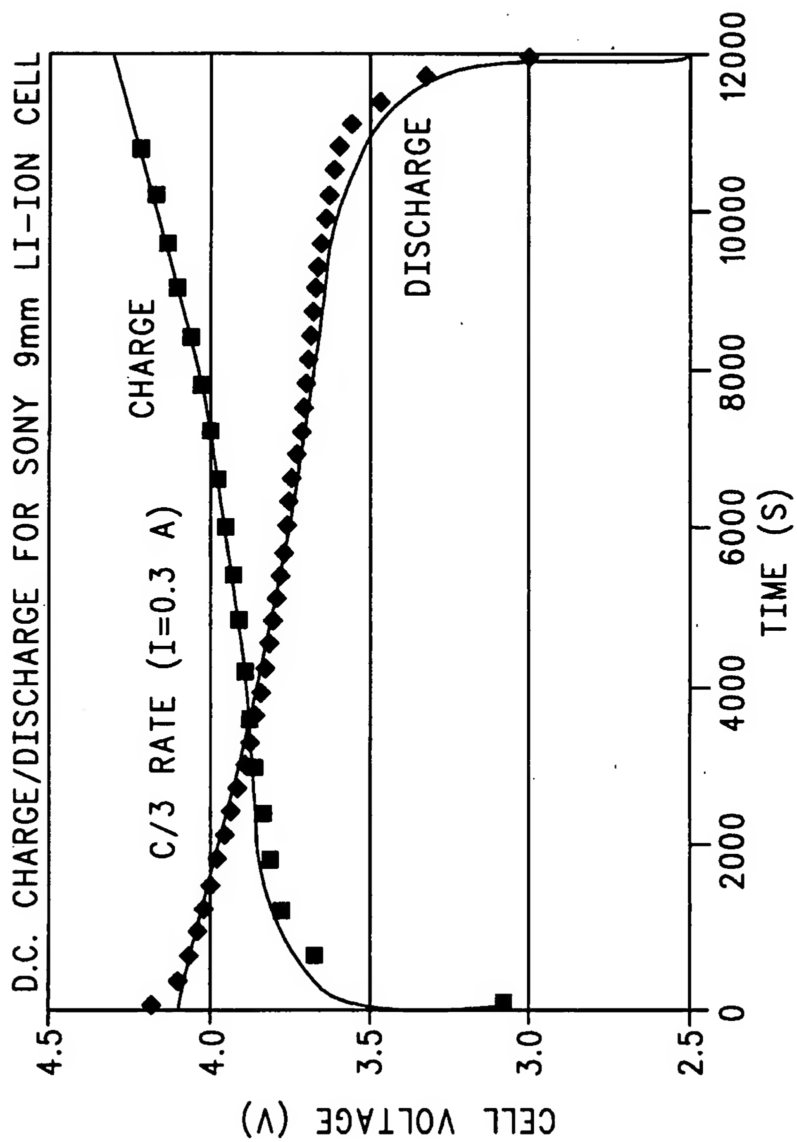
D.C. CHARGE/DISCHARGE FOR SONY 9mm LI-ION CELL
C/3 RATE (I=0.3 A)
CHARGE
DISCHARGE
CELL VOLTAGE (V)
4.5
4.0
3.5
3.0
2.5
TIME (S)
0
2000
4000
6000
8000
10000
12000

FIG. 5

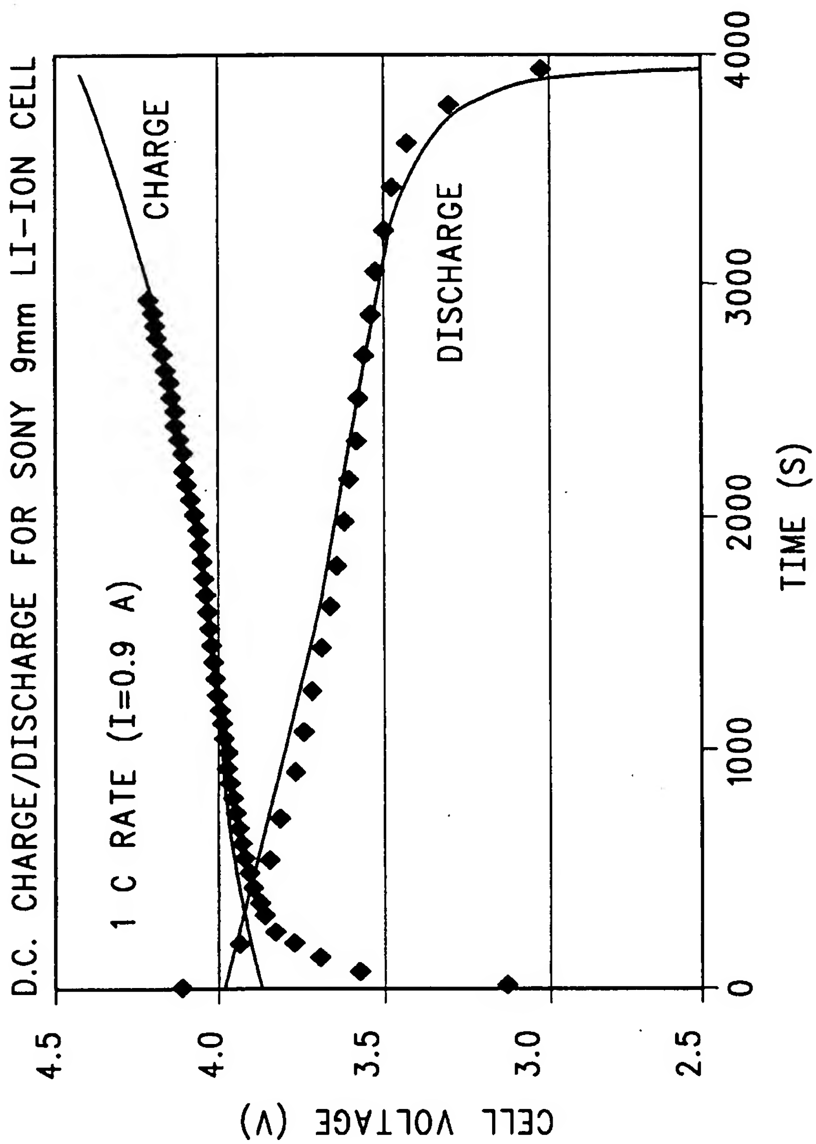
D.C. CHARGE/DISCHARGE FOR SONY 9mm LI-ION CELL
1 C RATE (I=0.9 A)
CHARGE
DISCHARGE
CELL VOLTAGE (V)
4.5
4.0
3.5
3.0
2.5
TIME (S)
0
1000
2000
3000
4000

FIG. 6

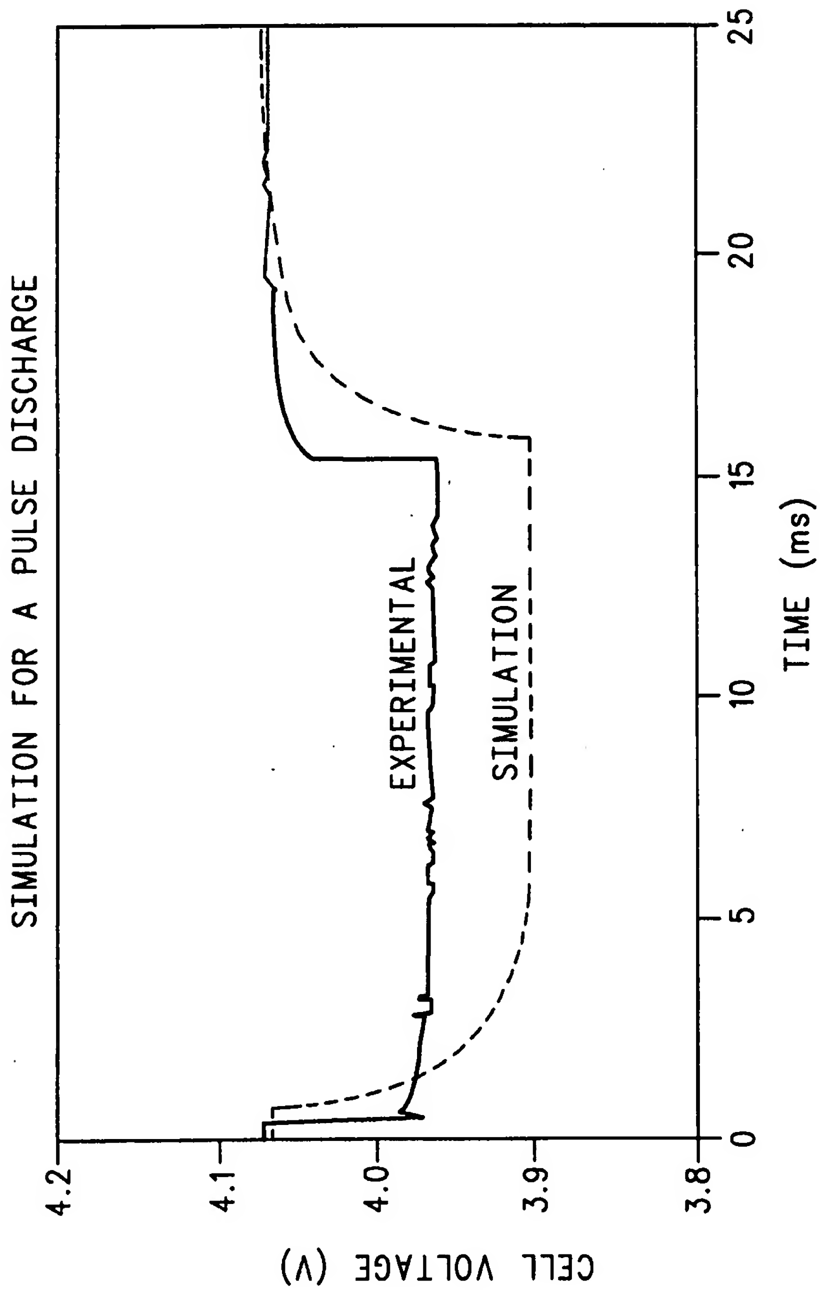
SIMULATION FOR A PULSE DISCHARGE
CELL VOLTAGE (V)
4.2
4.1
4.0
3.9
3.8
EXPERIMENTAL
SIMULATION
0
5
10
15
20
25
TIME (ms)

FIG. 7

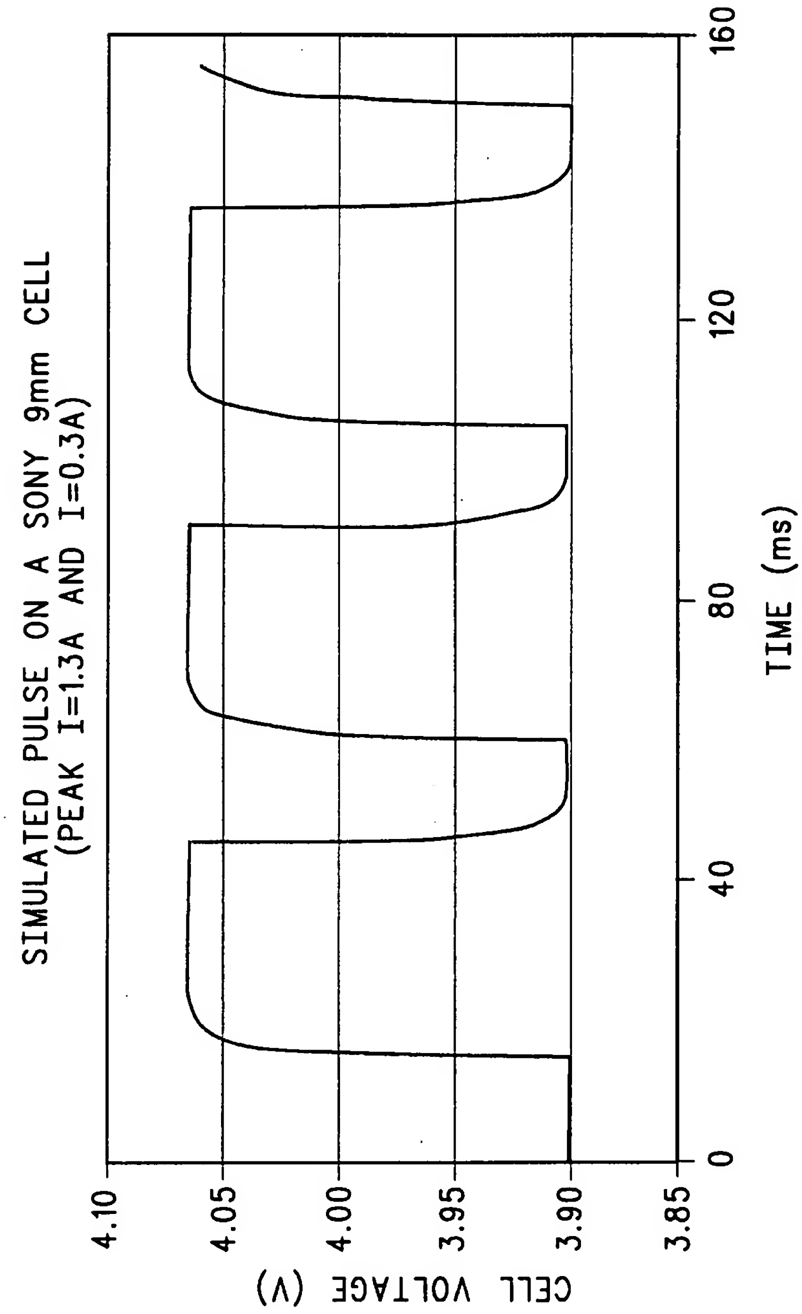
SIMULATED PULSE ON A SONY 9mm CELL
(PEAK I=1.3A AND I=0.3A)
CELL VOLTAGE (V)
4.10
4.05
4.00
3.95
3.90
3.85
0
40
80
120
160
TIME (ms)

FIG. 8

USER DEFINED PARAMETERS	MODEL DEVELOPER DEFINED PARAMETERS
CHEMISTRY:	THERMODYNAMIC RELATIONS:
LI-ION	Ueq+ = f(STATE OF CHARGE)
LI-POLYMER	Ueq- = f(STATE OF CHARGE)
Ni/MH	CONDUCTIVITY OF MATERIALS
MANUFACTURER	CONCENTRATION OF ELECTROLYTE
CAPACITY (Ah)	KINETIC CONSTANTS:
STATE OF CHARGING	EXCHANGE CURRENT DENSITY
TEMPERATURE	DIFFUSION COEFFICIENTS
CYCLE LIFE	DOUBLE LAYER CAPACITANCE
	MATERIAL RELATED PARAMETERS:
	PARTICLE SIZE
	SURFACE AREA
	DENSITY AND POROSITY
	BATTERY DESIGN PARAMETERS:
	ELECTRODE THICKNESS
	SEPARATOR THICKNESS
	PRACTICAL UTILIZATION FACTORS
	MASS RATIO

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/22455

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :G06F 17/50
US CL :703/4, 12; 320/128, 137
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 703/4, 12; 320/128, 137

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

US PATENTS, IEEE JOURNALS AND TRANSACTIONS

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

ONLINE SEARCHE, EAST/WEST, IEL
SEARCH TERMS: BATTERY, POWER, SIMULATION, MODELING, ELECTROCHEMICAL, CHARGE AND DISCHARGE RATE, TRANSPORT PROCESS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	US 6,016,047 A (NOTTEN ET AL.) 18 JANUARY 2000, COL. 2, LINES 23-67, COLS. 3-6, COL. 8, LINES 36-67, COL. 10, LINES 5-49, COLS. 12-24.	1-25
X	US 5,381,096 A (HIRZEL; EDGAR) 10 JANUARY 1995, ABSTRACT, COL. 2, LINE 33 TO COL. 3, LINE 20, COL. 4, LINES 13-62, COL. 8, LINES 6-46.	1-25
X	US 5,428,560 A (LEON ET AL.) 27 JUNE 1995, COL. 2, LINE 30 TO COL. 3, LINE 24, COL. 5, LINE 16 TO COL. 6, LINE 41.	1-25
Y	US 4,499,552 A (KANAZAWA, KAY) 12 FEBRUARY 1985, ENTIRE DOCUMENT.	1-25

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
11 OCTOBER 2000	17 NOV 2000

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/22455

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,945,806 A (FAULK, RICHARD) 31 AUGUST 1999, ENTIRE DOCUMENT.	1-25